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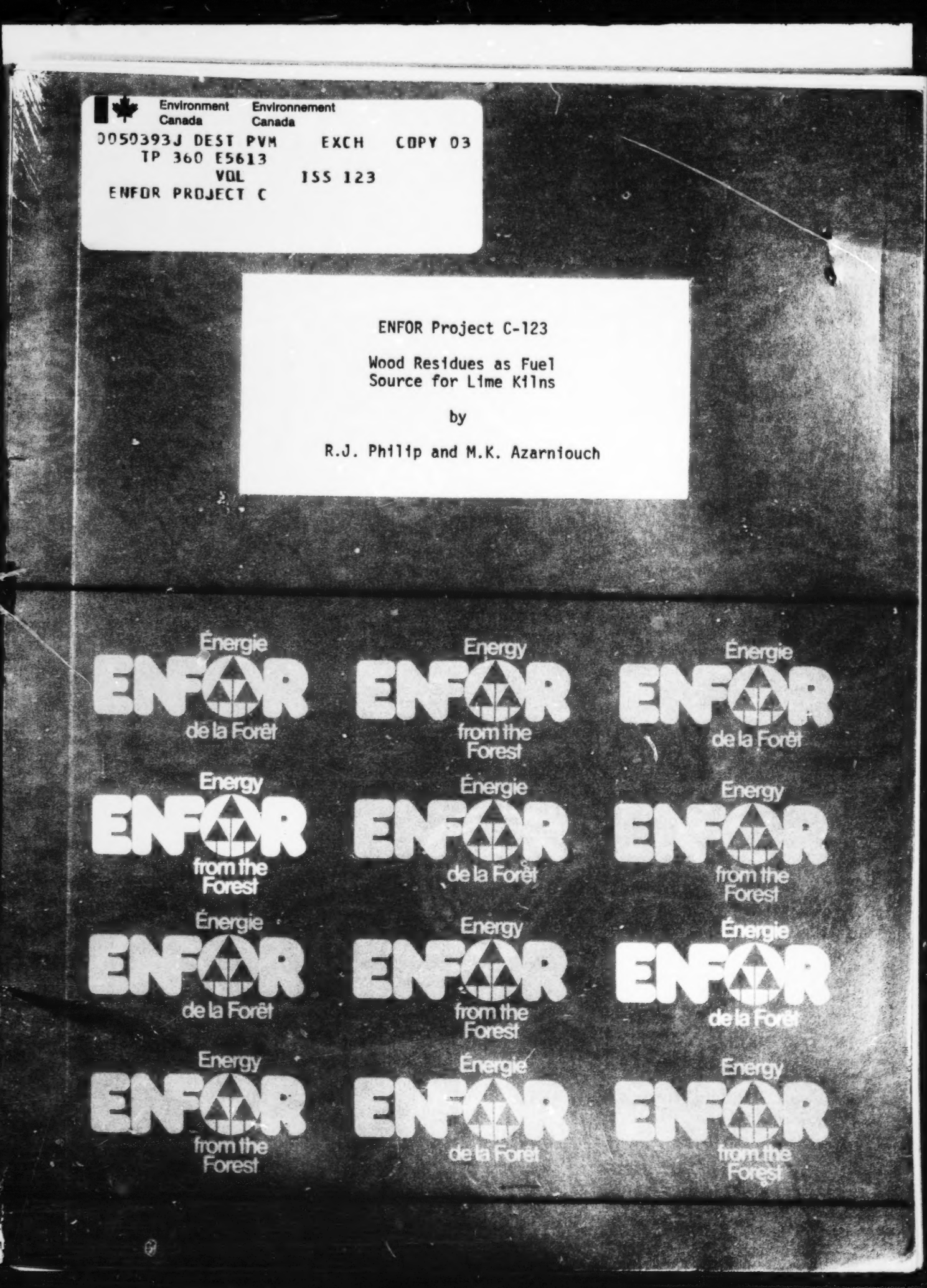
Wood Residues as Fuel Source for Lime Kilns

by

R.J. Philip and M.K. Azarniouch



Contractor's Final Report [1]
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ENFOR Project C-123

Wood Residues as Fuel Source for Lime Kilns

by

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November 1982

Tearsheet Annotation

Despite flow problems encountered with mill-produced lime mud, based on average product flow rates, a decrease in fossil fuel consumption of about 20% was achieved by feeding wet hog fuel into the cold end of a pilot lime kiln. Hog fuel ash contamination resulted in some reduction in lime quality. Because of the approximately three times higher "baseline" heat requirements per ton of CaO produced in the pilot kiln compared to the commercial kilns, significantly higher (30-50%) degree of substitution of fossil fuel might be achieved in pulp mills.

ABSTRACT

Despite flow problems encountered when feeding wet hog fuel with mill-produced lime mud directly into the cold end of a pilot kiln, a decrease in fossil fuel consumption of approximately 20%, based on long term average product flow rates, was obtained. The flow problems consisted of material adherence onto the kiln wall, increased dusting and feed-end losses.

The lime produced with hog fuel showed higher reactivity than lime produced without hog fuel. Upon causticizing a high-sulphidity mill green liquor, the equilibrium causticizing efficiency was not affected by the use of wood residues in calcining. However, there was some deterioration in the settling and filtration characteristics of the lime mud due to the presence of hog fuel contaminants.

The normal fuel requirement per ton of lime in mill kilns is only about one third of that in the pilot kiln. Because most of the problems and limitations encountered in the pilot kiln were associated with the very high mass ratio of hog fuel to lime mud required to achieve even 20% replacement, fossil fuel substitution of 30 to 50% might be attainable in commercial-scale lime kilns.

The ultimate goal of complete or near-complete substitution of fossil fuel by wood residues can be achieved by additional firing of dried (moisture content 10-15%) fines from the hot end of the kiln. Since this latter type of fuel is substantially more costly than wet, non-comminuted hog fuel, its usage should be minimized.

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WOOD RESIDUES AS FUEL SOURCE FOR LIME KILNS

FINAL REPORT

1. INTRODUCTION

One of the main obstacles to total energy self-sufficiency of kraft mills appears to be the fossil fuel requirements of the lime kilns (appr. 2 GJ/t of pulp). With an annual Canadian production capacity of 8.0 million tons kraft pulp, the fossil fuel requirements of all lime kilns are equivalent to about 2.5 million barrels of oil per year. If an appropriate technology can be developed which allows fossil fuel to be replaced nearly completely by wood-based fuel, the savings in fossil fuel by the pulp and paper industry would be substantial. In addition, the potential gross savings in fossil fuel cost would be equivalent to over $60 million/year.

Modern wood gasifiers, such as are being developed, have the potential to provide energy for the forest products industry operations. In principle, the prospect of an on-site wood gasification plant generating "producer gas" to displace natural gas or oil in the lime kiln of a kraft pulp mill is an attractive concept for using mill residues or forest biomass. However, capital cost figures are likely to be substantial. Also complete or near-complete replacement of fossil fuel by a low calorific value wood-gas appears to be highly unlikely, because of the substantial drop in the combustion gas temperature with this approach. In a more recent development, a combined "wet-cell" gasifier-burner marketed by Lamb-Cargate Industries Ltd. of New Westminister, B.C. has been successfully tested at MacMillan Bloedel's Port Alberni mill [1] for providing fuel to one of the three lime kilns in this mill.

In Phase I of this project, successful tests with fine granular limestone grit as the feed material and hog fuel as a partial source of the heat requirements were carried out. The results of these tests are

described elsewhere [2]. However, the use of lime mud (containing some NaOH and Na_2S) in that particular pilot kiln resulted in very severe material flow and handling problems including the inability of the exhaust system to handle all the gas flow, which were not inherent to the proposed process. They were largely associated with the design and operating characteristics of the small pilot kiln. Hence, it was decided to carry out additional pilot scale tests in Phase II of the project using a different and larger pilot kiln suitable for processing mill-produced lime mud, and having adequate exhaust gas handling capacity.

2. OBJECTIVES

There are two specific approaches possible to replace fossil fuel in lime kilns by direct combustion of wood residues:

(i) In-situ combustion of screened, but essentially coarse wood residues fed from the cold feed end of the kiln, and

(ii) direct firing of fine wood residues of low moisture content in suspension from the hot product end of the kiln.

In many situations, a combination of these two approaches, as shown in Figure 1, may be economically very attractive. Since the direct firing of fine wood residues in suspensions from the hot product end of the kiln can be considered established (although relatively expensive) technology [3], the objectives of Phase II of the study were to investigate the in-situ combustion approach in a pilot kiln using wet, uncomminuted hog fuel and mill-produced lime mud. Emphasis was to be placed on achieving substantial replacement of the fossil fuel and maintaining the throughputs and conversion efficiencies in the kiln. A further objective was to assess the possible adverse effects of inorganic contaminants and, if necessary, to develop and test corrective measures.

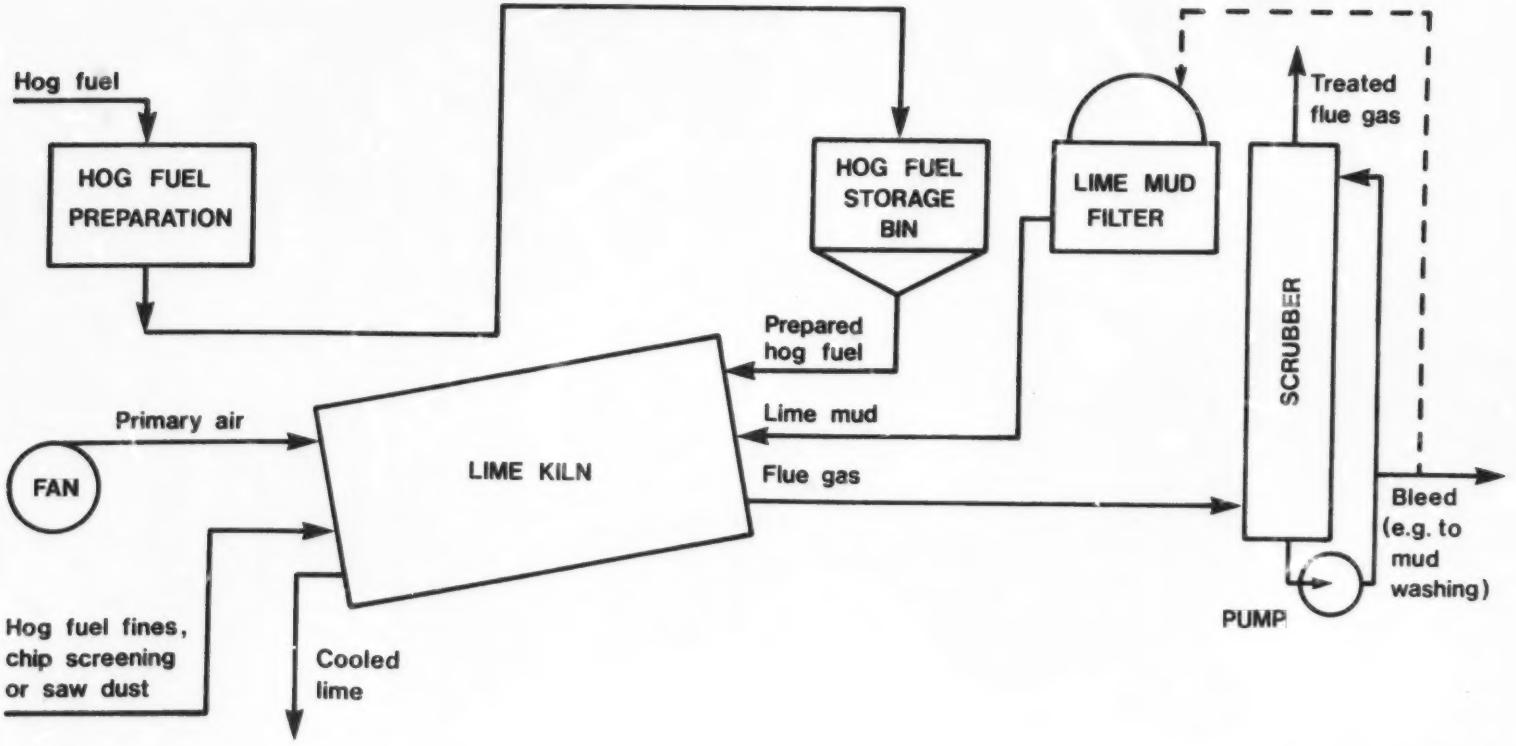

Figure 1. Schematic diagram of lime burning with hog fuel.

3. PILOT KILN STUDIES

3.1 Equipment

A rotary pilot kiln (0.9 m x 9.1 m, 0.7 m I.D.) of the Fuller Co. (Bethlehem, Pennsylvania) was used in Phase II of the studies. It had a slope of 1.8° and could be rotated between 0.4 and 2.1 RPM.

The kiln was fired with No. 2 fuel oil and the exhaust gases passed into a brick-lined settling chamber. The chamber collected the large particles from the gas stream as well as any material which fell off the feed end of the kiln. The exhaust gases then passed through duct work, a bag-house, and finally an I.D. exhaust fan. A water spray was located in the exhaust down-comer prior to the bag-house and was used intermittently to cool the exhaust gases below 200°C. This was the operating temperature limit of the NOMEX filter bags.

The feed and drying sections of the kiln contained respectively 0.6 m of spirals and 1.8 m of chains. The chain section contained six rows of chains with three chains per row. The chains were 0.41 m long and were made of links which were 2.5 cm long.

The material temperature in the hot zone of the kiln was measured with a 2.4 m long chromel-alumel thermocouple placed in the kiln load. The gas temperature in the kiln was measured at 4 locations: 2.6 m, 4.0 m, 5.0 m, and 6.3 m from the kiln discharge port by chromel-alumel thermocouples. The exhaust gas temperature was measured at the drop-out chamber, the bag-house inlet and the exhaust fan inlet using similar thermocouples.

The oxygen and combustibles concentrations were measured at the feed end of the kiln by a Teledyne O_2 analyzer. A port was also used to collect gas samples for chromatographic analyses.

Lime mud and hog fuel were both fed into the kiln by a hydraulic ram feeder which drove a 0.2 m diameter hardened steel head which pushed material into a 1.37 m tapered (2.12°) feed pipe and into the kiln.

The kiln product was collected in a drum placed under the discharge port. Drop-out and bag-house products were collected in a similar manner.

It should be noted that this pilot kiln differed from a mill kiln in several important ways, which gave a bearing on interpreting the findings.

(i) feed system: hand fed hydraulic ram instead of screw feeder
(ii) chain system: low density
(iii) product handling: lime discharge directly into drums
(iv) flue gas exhaust system:
  (a) bag house instead of scrubber for particulate collection
  (b) addition of water spray for exhaust gas temperature reduction
(v) high exhaust gas temperature (before water spray): 400°C (cf. 200°C).
(vi) low L/D ratio: 13:1 (cf. 30:1)

and, as a consequence of most of the above,

(vii) high "baseline" fossil fuel consumption: 33 to 56 GJ/t CaO in product (cf. 10-13 GJ/t)

3.2 Test Runs

Two test runs (I and II), each of one week duration, were conducted. The lime mud used in both test runs was produced by a kraft mill with no lime recovery, hence using 100% purchased lime. Although the levels of impurities in the mud were not atypical, the reactivity of the lime produced by the pilot kiln (fossil fuel firing only) was low.

3.2.1 First Test Run

In the first test run (I) lime mud (moisture ~30%) was fed along with 11 kg/h of a calcium carbonate grit (2-3 mm diameter) to simulate the calcium make-up in a mill environment. A wood residue produced in a lumber mill by dry debarking was used for the in-situ combustion. Over 80% of this material were particles which exceeded 0.6 cm in size and strips of bark up to 20 cm in length were also present. The

average ash content was 6% (dry basis) and the average moisture content was 46%. An analysis of the wood ash is given in Appendix A.

A summary of operating conditions and results is presented in Table I.

3.2.1.1 Material Flow

Firing fossil fuel only (run I-0) resulted in the formation of a pebble lime with particle sizes up to approximately 5 cm in diameter. There was very little dust present in the product. A slight build-up of material on the refractory and ring formation occurred near the product discharge port. This is typical of pilot kiln processing and the material was removed intermittently by scraping.

During the runs I-1 and I-2, wood residue was fed at rates of 40 and 119 kg/h (wet basis). Pebble lime was no longer formed even at the lower feed rate and this resulted in severe dusting. Build-up of material on the kiln refractory to a depth of 2 to 10 cm occurred over the entire length of the kiln and ring formation was evident. Although small quantities of the coating dropped off during the operation, the kiln required regular scraping. At a wood residue feed rate of 119 kg/h there was a flaming combustion over most of the length of the kiln with complete burn-out approximately 0.6 m from the discharge. The wood residue ignited in the feed section of the kiln.

During the runs I-3 and I-4, the wood residue was fed at 97 and 140 kg/h (wet basis). At both feed rates, char was discharged with the product and severe dusting and accumulations in the bag-house resulted in reduction of the stack oxygen concentration, from 4% to under 1%. Concurrently the combustibles increased from under ½% to approximately 4%. However, during this phase of the test run there was very little accumulation of material on the kiln refractory.

Feeding the wood residue to the kiln from the cold end also caused an increase in feed 'drop-out' and bag-house particulate collection

TABLE I

SUMMARY OF OPERATING CONDITIONS AND RESULTS OF THE FIRST TEST RUN

Run No.	I-0	I-1	I-2	I-3	I-4
Lime mud plus $CaCO_3$ grit feed rate[1], kg/h (as-is)	195	156	184	220	159
Wood residue feed rate, kg/h (as-is, wet basis)	0	40	119	97	140
Oil firing rate, GJ/h	1.77	1.59	1.09	1.09	1.07
Kiln rotational speed, rpm	1.0	1.0	1.5	2.0	2.0
Reduction in oil firing rate[2], %	NA[4]	10	38	38	39
Production rate, kg/h (as-is, dry basis)	63	29	41	46[6]	37[6]
Product available lime index, %	86	85	80	80	65
Feed end drop out rate, kg/h (as-is, dry basis)	7	10	28	18	13
Bag house particulates collection rate, kg/h (as-is, dry basis)	2	9	12	30	30
Fossil fuel consumption, GJ/t CaO in product	32.7	64.5	33.2	32.9[7]	49.4[7]
Change in fossil fuel consumption[2], %	NA[4]	+97.2	+1.5	+0.9	+52.9
Hog fuel utilization[3], %	NA[4]	42	54	66	46
Exhaust gas temperature, °C	385	405	615	500	700
Increase in actual exhaust gas flow[2], %	NA[4]	18	120[5]	25[5]	97[5]

1) Lime mud moisture content ∿30%, $CaCO_3$ grit feed rate 11 kg/h (dry)

2) Relative to oil-firing-only case

3) Ratio of reduction in heat input by oil to heat input by hog fuel

4) NA - not applicable

5) Apparent inconsistencies are due to differences in excess air

6) Product was contaminated with char.

7) Char-free basis.

rates. In order to minimize the former, the kiln rotational speed was increased from 1 RPM to 2 RPM. Relative to the 'baseline' (I-0) case the kiln drop-out rate increased from 5% to 19% and the bag-house particulates carryover rate increased from 2% to 9% when wood residue was fed at 119 kg/h.

3.2.1.2 Fuel Consumption

During runs I-1 and I-2, as the wood residue feed rate was increased to 119 kg/h, the fossil fuel firing rate was reduced to 1.09 GJ/h which was 62% of the base case oil firing rate. However, the fossil fuel consumption, based on the average measured product flow rate* and the "available lime index" (i.e. GJ/t of "available" lime actually collected as product), did not decrease hence no real fossil fuel savings appear to have been achieved (see Table I). Although the fossil fuel consumption did not decrease, it should be noted that the combustion of the wood residue assisted in the calcination of the lime since a product with an unacceptably low availability would have been produced without the addition of the wood residue.

The apparent increase in the fuel consumption can be attributed to a reduction in the product flow rate because of dusting and accumulation as well as a slight reduction in the "available lime index" of the product (from 86 to 80%).

3.2.1.3 Kiln Temperatures

The replacement of fossil fuel by the in-situ combustion of wood residue resulted in an increase in the temperatures in the feed and middle sections of the kiln. As the wood residue feed rate increased from 40 to 140 kg/h, the increase in the exhaust gas temperature, over that of the fossil fuel only case, went from 20°C to 315°C which corresponded to 5% and 30% of the total heat input of the residue.

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* Each product flow rate measurement over a particular phase of the operation of interest was reduced to a corresponding flow having a 0% loss on ignition. The average was determined and converted to a flow using the loss on ignition obtained at the lowest fossil fuel firing rate during that phase.

The kiln temperature profiles and a summary of mass and heat balance calculations are given in Appendix A.

3.2.1.4 Contamination

The in-situ combustion of wood residue resulted in an increased input of inorganic contaminants and increased dusting which affected the composition of the product, drop-out and bag-house streams. The concentration of the inorganic elements for these streams are given in Table II. Since the increases in the concentrations were not linear functions of the wood residue feed rate, dusting is likely to have had an impact.

3.2.2 Second Test Run

In the second test run (II) lime mud was the sole source of carbonate fed to the kiln. The calcium carbonate grit was eliminated due to the difficulty in feeding both components at a constant rate. The mud used during the test was from the same source as before but was collected at a different time and total soda content was lower (2.1% Na_2O compared to 2.6%). When firing only oil, this material did not produce pebble lime to the same extent as the one used in the first test run hence the rate of dust carry-over to the bag-house was greater.

Due to the deterioration in lime quality and the presence of char in the product in the first run, the wood residue was considered unsatisfactory in terms of cleanliness and particle size. Therefore a screened (accepts: 0.6 to 8 cm, see Appendix B) kraft mill hog fuel from wet debarking was used in the second test run. The average moisture content was 40% and the average ash content was 4% (dry basis); an analysis of the wood ash is given in Appendix B. The in-situ combustion of Woodex*, a commercially available pelletized biomass fuel, was investigated during the last 24 hours of the test run. This allowed a preliminary assessment of the effects of particle size uniformity and of material dryness.

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* Woodex is manufactured by BioShell Inc.

TABLE II

ANALYSES (X-RAY) OF THE VARIOUS STREAMS OF THE FIRST TEST RUN

Values reported are averages and were determined on samples which were ignited in a muffle furnace to obtain loss on ignition.

Material	CaO (%)	MgO (%)	Fe_2O (%)	SiO_2 (%)	Al_2O_3 (%)	K_2O (%)	MnO (%)	P_2O_5 (%)	SO_3 (%)	Na_2O (%)
Lime Mud Feed	92.72	1.06	0.28	1.90	0.53	0.09	0.04	0.10	0.74	2.62
Product:										
I-0	93.29	1.14	0.29	1.75	0.49	0.06	0.04	0.11	0.67	2.03
I-2	85.66	1.31	0.72	7.08	1.53	0.45	0.09	0.19	0.47	2.86
I-4	81.04	1.32	1.22	13.56	2.74	1.11	0.14	0.28	0.19	2.62
Drop Out:										
I-0	91.47	1.14	0.39	1.90	0.77	0.07	0.04	0.14	1.33	2.76
I-2	90.15	1.21	0.60	4.12	1.44	0.20	0.10	0.17	0.56	2.22
I-3	90.58	1.15	0.51	3.80	0.96	0.16	0.06	0.14	0.82	1.77
I-4	83.30	1.29	0.92	8.98	1.98	0.51	0.12	0.25	0.48	2.13
Bag House:										
I-0	87.50	1.07	0.71	1.49	0.62	0.19	0.04	0.12	3.79	4.35
I-2	91.44	1.11	0.50	1.39	0.57	0.20	0.06	0.14	1.94	2.65
I-3	93.21	1.10	0.31	1.88	0.55	0.08	0.05	0.12	0.98	1.68
I-4	90.96	1.07	0.50	2.13	0.60	0.14	0.06	0.14	1.74	2.62
Accum.[1]	91.98	1.05	0.33	1.60	0.47	0.13	0.05	0.13	1.80	2.43

[1] Material accumulated in the bag house

3.2.2.1 Material Flow

Compared with the first test run a decrease occurred in the production of pebble lime when firing only fossil fuel which resulted in a product consisting of approximately 70% pebbles or granules and the remainder dust. There was also a slight tendency of the material to form a ring near the product discharge port therefore the kiln was scraped intermittently.

Feeding hog fuel at a rate of 28 kg/h caused a reduction in the pebble formation; approximately 50% of the product was now granular. The kiln load was light and the material did not appear to flow freely down the kiln. Material also coated the kiln in a 0.9 m wide band located approximately 2.1 to 3.0 m from the discharge. The band or ring built up to a thickness of approximately 8 cm. The hog fuel burned out completely in the feed and chain-section of the kiln.

As the hog fuel feed rate was increased to 50 kg/h the quantity of lime granules was reduced to between 10% and 20% of the total discharge. The kiln loading was variable in this case. Material coated the kiln from the chain section to the discharge port to a thickness of approximately 10 cm. Small quantities of the coating dropped off from the refractory during normal operation, but when the temperature dropped (e.g. upon reducing the oil firing rate), substantial loss of the coating occurred. The kiln was scraped regularly from its middle section to its discharge. The hog fuel burned with a flame to within 3 m of the discharge port and burned out approximately 0.6 m from it. A photograph of the interior of the kiln when firing hog fuel at a rate of 67 kg/h is shown in Figure 2.

A summary of operating conditions and results is presented in Table III.

Feeding hog fuel to the kiln again caused an increase in the drop-out and bag-house flow rates. In order to control the quantity of material which was lost by the former the kiln speed was increased from

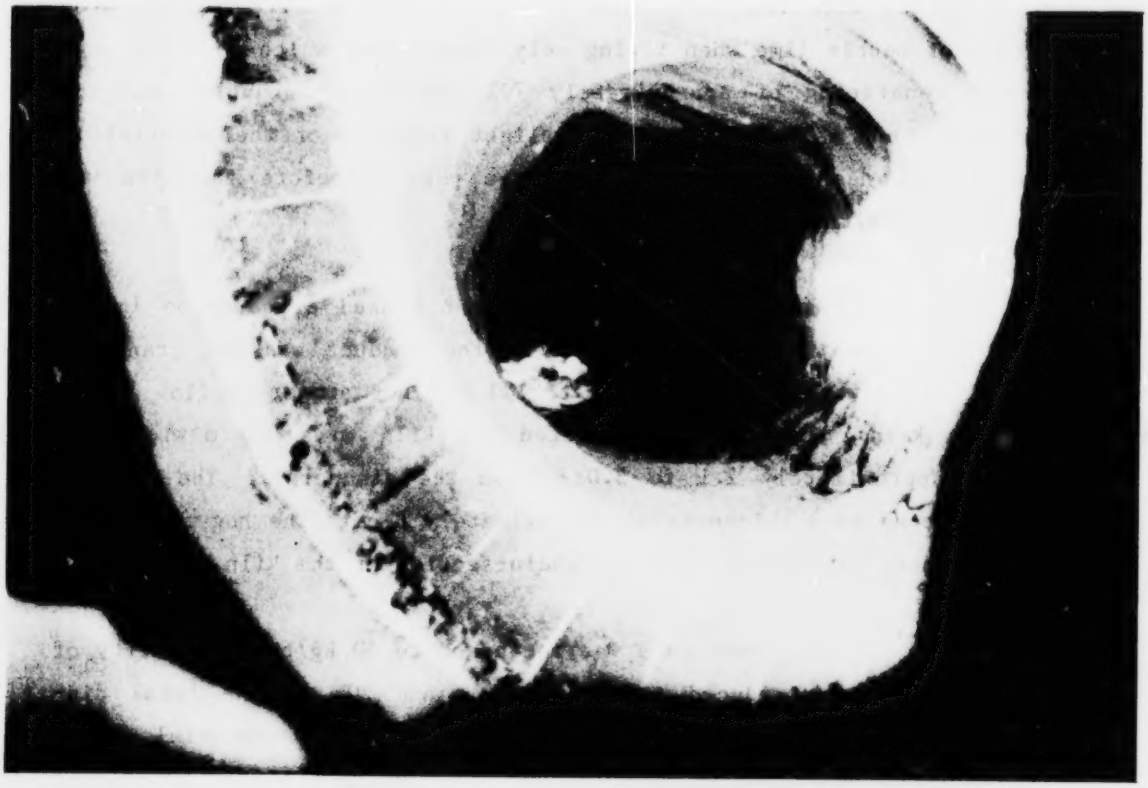

Figure 2. Interior of the pilot lime kiln during in-situ combustion of 67 kg/h of hog fuel (run II-3).

TABLE III

SUMMARY OF OPERATING CONDITIONS AND RESULTS OF THE SECOND TEST RUN

Run No.	II-0	II-1	II-2	II-3	II-4
Lime mud feed rate[1], kg/h (as-is,wet basis)	135	149	146	159	144
Wood residue feed rate, kg/h (as-is,wet basis)	0	28	50	67	101
Oil firing rate, GJ/h	1.77	1.49	1.29	1.22	1.09
Kiln rotational speed, rpm	1.0	1.0	1.5	2.0	2.0
Reduction in oil firing rate[2], %	NA[4]	15	27	31	38
Production rate, kg/h (as-is, dry basis)	38.1	33.6	31.3	31.8	29.5
Product available lime index, %	83	86	84	83	84
Feed end drop out rate, kg/h (as-is, dry basis)	6.4	10.4	13.2	12.7	23.6
Bag house particulates collection rate, kg/h (as-is, dry basis)	5.0	6.8	11.8	16.3	19.5
Fossil fuel consumption, GJ/t CaO in product	56.0	51.6	49.1	46.2	44.0
Change in fossil fuel consumption[2], %	NA[4]	-7.9	-12.3	-17.5	-21.4
Hog fuel utilization[3], %	NA[4]	86	90	66	62
Exhaust gas temperature, °C	410	450	500	560	680
Increase in actual exhaust gas flow[2], %	NA[4]	11	21	44	80

1) Lime mud moisture content ∿30%

2) Relative to oil-firing-only case

3) Ratio of reduction in heat input by oil to heat input by hog fuel

4) NA - not applicable.

1 RPM for fossil fuel firing only to 1.5 RPM at 50 kg/h of hog fuel and to 2 RPM at higher hog fuel feed rates. Based on dry feed input rate the drop-out rate increased from 7% to 23% and the bag-house rate increased from 5% to 19% at a hog fuel feed rate of 101 kg/h and a kiln rotational speed of 2 RPM.

The in-situ combustion of Woodex resulted in flow conditions which were similar to the above but now 40% to 50% of the product was granular. The drop-out and bag-house flow rates averaged 10% and 17%, respectively, of the dry feed input rate and a significant portion of the material was CaO.

Difficulties with the kiln draft did not occur during this test run and the stack oxygen was maintained at approximately 5%. The gas-phase combustibles during hog fuel and Woodex operation were under 1%.

3.2.2.2 Fuel Consumption

The results of the second test run were similar to those of the first in that the fossil fuel firing rate was reduced to 1.09 GJ/h, which was again 62% of the base case firing rate, as the hog fuel feed rate was increased to 101 kg/h. However, the fossil fuel consumption (GJ/t) determined for each product flow measurement (2 h time interval) did not decrease and no fossil fuel savings (in terms of fuel/t of CaO collected) were realized (see Appendix B). Although the combustion of the hog fuel assisted in the calcination of the lime, the major problem was again the reduction in the product flow rate mainly due to accumulation in the kiln, in addition to bag-house and drop-out losses.

In order to eliminate the short term (4h) variability in the product flow rate the long term average was also determined. The results are given in Table III* and in this case show fuel savings. It should be noted that the averaging tends to bias the results in favour of

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* See Appendix B for additional information.

higher product rates and hence lower fossil fuel consumptions (GJ/t). This was due to the high product discharge rates which occurred when the temperature profile collapsed and material was released from the kiln refractory. The fuel savings are therefore only an indication of what might have been achieved if flow conditions had been better. The trend in the fossil fuel consumption may, however, be applicable to a mill kiln in which during long term operation material will probably not accumulate on the refractory and under normal operating conditions a near constant product flow rate is maintained.

Based on the average measured product flow rate a 21% reduction in the fossil fuel consumption was obtained at a hog fuel feed rate of 101 kg/h (wet basis). Since the mass balance at this feed rate was not consistent with those for other rates, a 17% reduction obtained at a hog fuel feed rate of 67 kg/h is likely to be a more reliable value. The use of Woodex resulted in an increase in the fossil fuel consumption of over 11%, due mostly to substantial heat losses in the exhaust gas.

The product flow rate decreased as the hog fuel feed rate increased. The maximum decrease was 23% at a hog fuel feed rate of 101 kg/h, (with Woodex the decrease was 38%). The available lime index reached a maximum of 87% for fossil fuel only and 85% for a hog fuel feed rate of 67 kg/h (see Appendix B, Table B-I). Therefore, the fossil fuel consumption was affected mainly by flow conditions and to a lesser extent by product quality. Although in-situ combustion of hog fuel allowed a reduction in the fossil fuel firing rate (when averages were considered), the average product discharge rate varied inversely with the hog fuel feed rate.

3.2.2.3 Kiln Temperatures

The replacement of fossil fuel by the in-situ combustion of hog fuel resulted in an increase in temperatures in the feed and middle sections of the kiln and a decrease in the discharge section. Tempera-

ture profiles in the kiln for various hog fuel feed rates are shown in Figure 3. It should be noted that these were thermocouple measurements which were affected (to a variable extent) by material coating the thermowells during the hog fuel operation. Replacement of both the thermocouple and sheath at the 6.3 m location during the test indicated that the coating could cause a 180°C lower reading in the measured temperature.

The heat input required to raise the exhaust gas temperature above that of the fossil fuel only case represents a loss and when related to the total heat input of the hog fuel it can be used as an indicator of the value of hog fuel for in-situ combustion. As the hog fuel feed rate increased the fraction of its heat input which caused an increase in the exhaust gas temperature also increased. The results are given in Table III. As the hog fuel feed rate increased from 28 to 101 kg/h the increase in the exhaust gas temperature, over that of the fossil fuel only case, went from 40°C to 270°C which corresponded to 17% and 35%, respectively, of the associated hog fuel input. A summary of the mass and heat balance calculations is given in Appendix B.

The use of Woodex resulted in even larger temperature increases in the feed section and exhaust of the kiln (see Appendix B). A feed rate of 85 kg/h caused a 380°C increase in the exhaust temperature which represented 30% of the total heat input of the Woodex.

3.2.2.4 Contamination

As in the first test run, the in-situ combustion of hog fuel affected the quality of the product, drop-out and bag-house streams by the introduction of inorganic contaminants. The concentration of inorganic elements for these streams is given in Table IV for a hog fuel feed rate of 67 kg/h.

Although in-situ combustion of hog fuel caused increases in the concentrations of the inorganic contaminants in the product stream those increases were not as great as in the first test run (based on

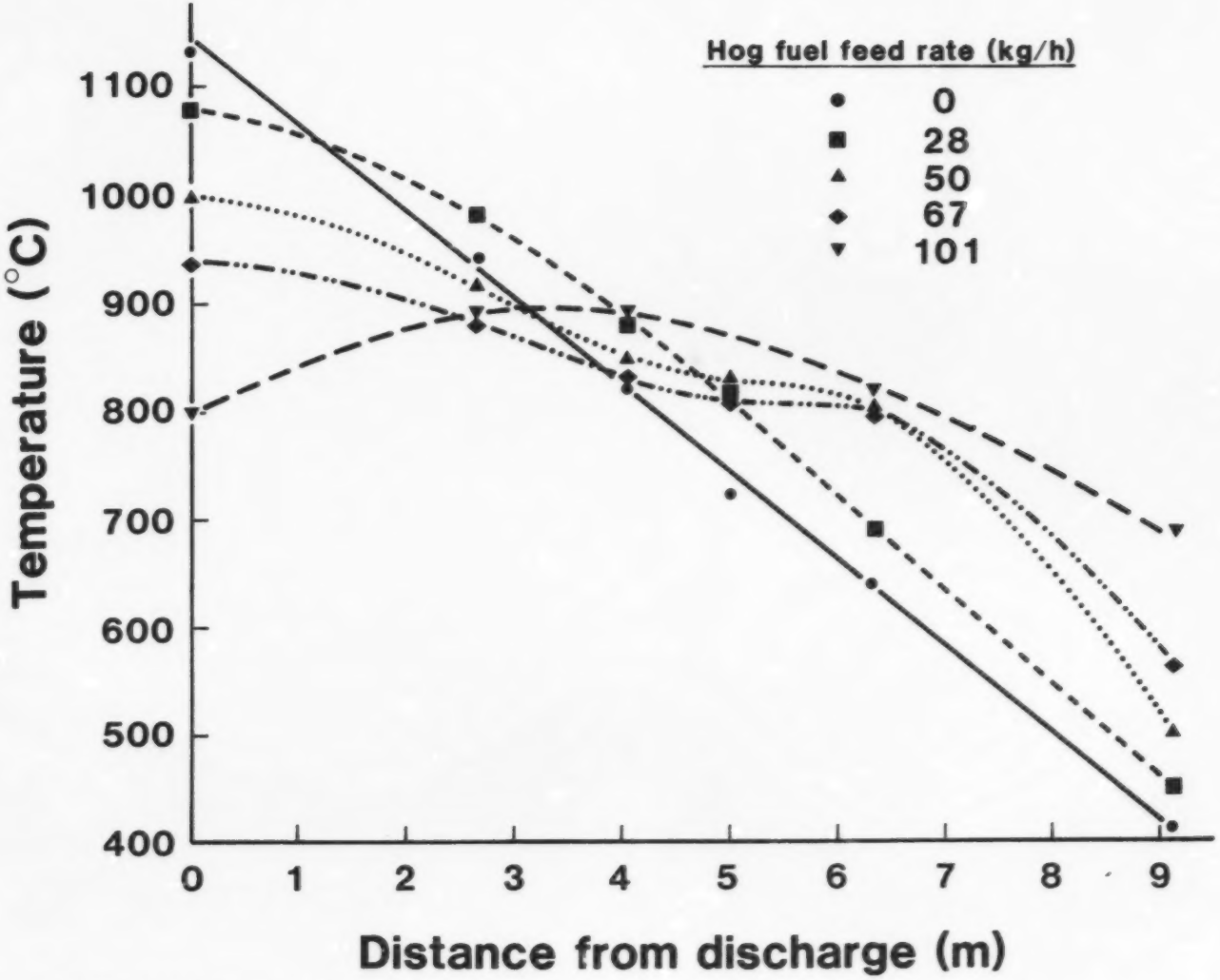

Figure 3. Kiln temperature profile during the in-situ combustion of hog fuel in the second test run. Sheathed thermocouples projecting into the gas phase were used in all measurements except at the discharge end. In this case the thermocouple was placed in the kiln load. All thermocouples (except at discharge end) were subject to coating to varying extents and were hence registering lower values (possibly up to 180°C).

TABLE IV

ANALYSES (X-RAY) OF THE VARIOUS STREAMS OF THE SECOND TEST RUN

Values reported are averages and were determined on samples which were ignited in a muffle furnace to obtain loss on ignition.

Material	CaO (%)	MgO (%)	Fe_2O (%)	SiO_2 (%)	Al_2O_3 (%)	K_2O (%)	MnO (%)	P_2O_5 (%)	SO_3 (%)	Na_2O (%)
Lime Mud Feed	92.39	1.23	0.38	2.39	0.69	0.19	0.06	0.12	0.75	2.10
Product:										
II-0	91.76	1.31	0.44	2.91	0.77	0.15	0.07	0.09	0.65	1.77
II-3	90.77	1.41	0.62	3.39	0.82	0.31	0.09	0.24	0.47	1.94
Drop Out:										
II-0	91.63	1.34	0.53	2.55	0.73	0.22	0.06	0.09	1.08	2.04
II-3	92.40	1.35	0.42	2.02	0.71	0.27	0.08	0.17	0.88	1.89
Bag House:										
II-0	90.56	1.58	1.10	2.54	0.72	0.21	0.08	0.09	1.16	2.16
II-3	92.61	1.19	0.40	1.24	0.57	0.25	0.06	0.17	1.47	1.96

normalized values so that the hog fuel-wood residue feed rates were not variables). The use of screened hog fuel (with the -0.6 cm and +8 cm fractions removed) compared to saw mill wood residue resulted in substantial reductions in the input rates of the inorganic contaminants. The relative cleanliness of the material had an obvious positive impact upon product quality. Hog fuel, which was produced in a wet debarker and then screened (both the fines and coarse fractions removed), had a lower dirt content than the sawmill wood residue, produced by dry debarking; therefore the deterioration in the product quality was smaller.

3.3 Product Quality Studies

3.3.1 Slaking Studies

The reactivity of the limes produced in the pilot kiln test runs was determined by measuring the slaking rate (ASTM C 110-58). For both test runs the lime produced using only fossil fuel had a low reactivity while the lime produced using the wood residues had a medium reactivity. The difference was due to the increased over-burning in the lime produced with only the fossil fuel firing. This was confirmed by electromicrographs which showed increased fusion of the crystallites in the lime produced with only fossil fuel, compared with that from fossil fuel and wood residues. Since pilot kilns tend to over-burn lime (due to the low length to diameter ratio) this difference in reactivity may not occur in a mill environment).

3.3.2 Causticizing Studies

The kiln produced limes were used to causticize a high-sulphidity, kraft mill green liquor (AA = 57, EA = 43, TTA = 132, where the concentrations are reported as g of Na_2O/L*). Since excess lime is known to reduce the settling rate of lime mud [4-6], the lime to green liquor ratio used in the causticizing was only sufficient to produce equili-

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* AA: active alkali, EA: effective alkali, TTA: total titratable alkali

brium conditions. The lime requirements were estimated by using the equilibrium curves for white liquor [7,8]. By this method the quantity of lime would not limit the conversion of the green liquor into white liquor and the effects of excess lime on the settling rate would be minimized.

The causticizing was conducted in a 500 mL batch reactor at a temperature of 95°C for a duration of two hours. The entire contents of the reactor were then transferred to a 500 mL settling cylinder and the settling characteristics were determined at 95°C by recording the height of the lime mud-white liquor interface with time. A sample of white liquor was analyzed and further settling and filtration tests were conducted. The lime mud was then wet screened.

3.3.2.1 Equilibrium Causticizing Efficiency

The equilibrium causticizing efficiency was not adversely affected by the use of either sawmill wood residues or kraft mill hog fuel.

3.3.2.2 Settling

The surface area requirements and operation of a continuous thickener may be assessed by a series of batch settling experiments in which the slurry solids concentration is varied. The downward flux of solids can be determined by measuring the initial velocity of the lime mud-white liquor interface for a given slurry solids concentration. This flux is shown in Figure 4 as a function of the solids concentration for lime muds which were produced from limes from the second test run. The use of hog fuel in the calcination of the lime resulted in a reduction in the solids flux (approximately 45%) over the entire slurry concentration range studied. Sawmill wood residue used in the first test run caused an even larger reduction (approximately 65%). This would necessitate a reduction in either the capacity of the thickener (white liquor clarifier) or in the solids concentration in the under-flow. The settling characteristics of lime mud in water (80°C) were similar to those in the white liquor (approximately 35% reduction) therefore a lime mud washer could be affected in a corresponding manner.

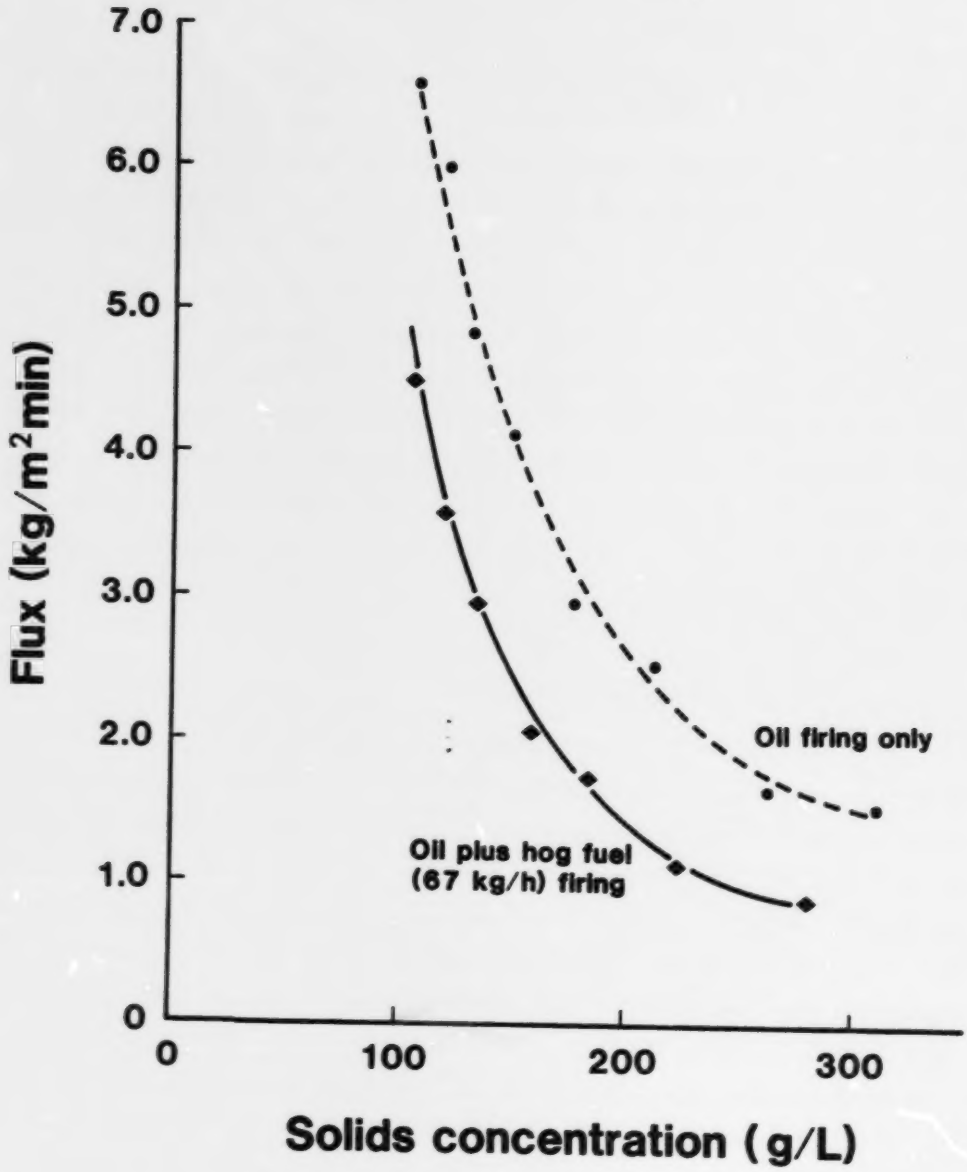

Figure 4. The effects of hog fuel contamination on the solids flux in white liquor. Limes produced in the second test run were used in the causticizing.

The above analysis for a continuous thickener does not take into consideration its depth requirements. A continuous or possibly a semi-continuous procedure is required for proper analysis [9].

3.3.2.3 Filtration

The filtration characteristics of the lime mud were assessed using the procedures given in reference [10] and a pour-on type of test leaf. The calculation of the bed permeability was based on Darcy's law [5]. The use of sawmill wood residue and hog fuel to calcine lime mud resulted in an increase in the bed formation time (10-20%) and bed height (10-40%). However, the lime mud bed tended to crack and the permeability was not significantly affected. The bed moisture content (after pulling air through it for 10 min.) also increased (10-30%). It appears that the operation of a vacuum filter might be adversely affected which could result in an increase in the moisture content of the lime mud fed to the kiln. This could result in increased kiln fuel costs and possibly in operating difficulties (if exhaust capacity is exceeded).

3.3.2.4 Lime Mud Particle Size

The cumulative particle size distribution was determined for the lime muds in order to assess the ease with which the inorganic contaminants could be removed from a mill system. Wood residues used in the production of lime caused an increase in the fraction of lime mud particles exceeding 60 mesh for both test runs. For the first test run the increase was from 0.7% (fossil fuel only) to 7.2% (wood residues) while for the second test run the increase was from 1.4% (fossil fuel only) to 2.7% (hog fuel). The cumulative size distribution for the last test run is shown in Figure 5. Although there were differences in the wood residue feed rates for the two test runs the cleanliness of the biomass has had an impact upon the size distribution.

In a mill environment the use of wood residues in calcination could result in significant increases in the production of "grits" which would be removed by the slaker-classifier [8] and hence act as a

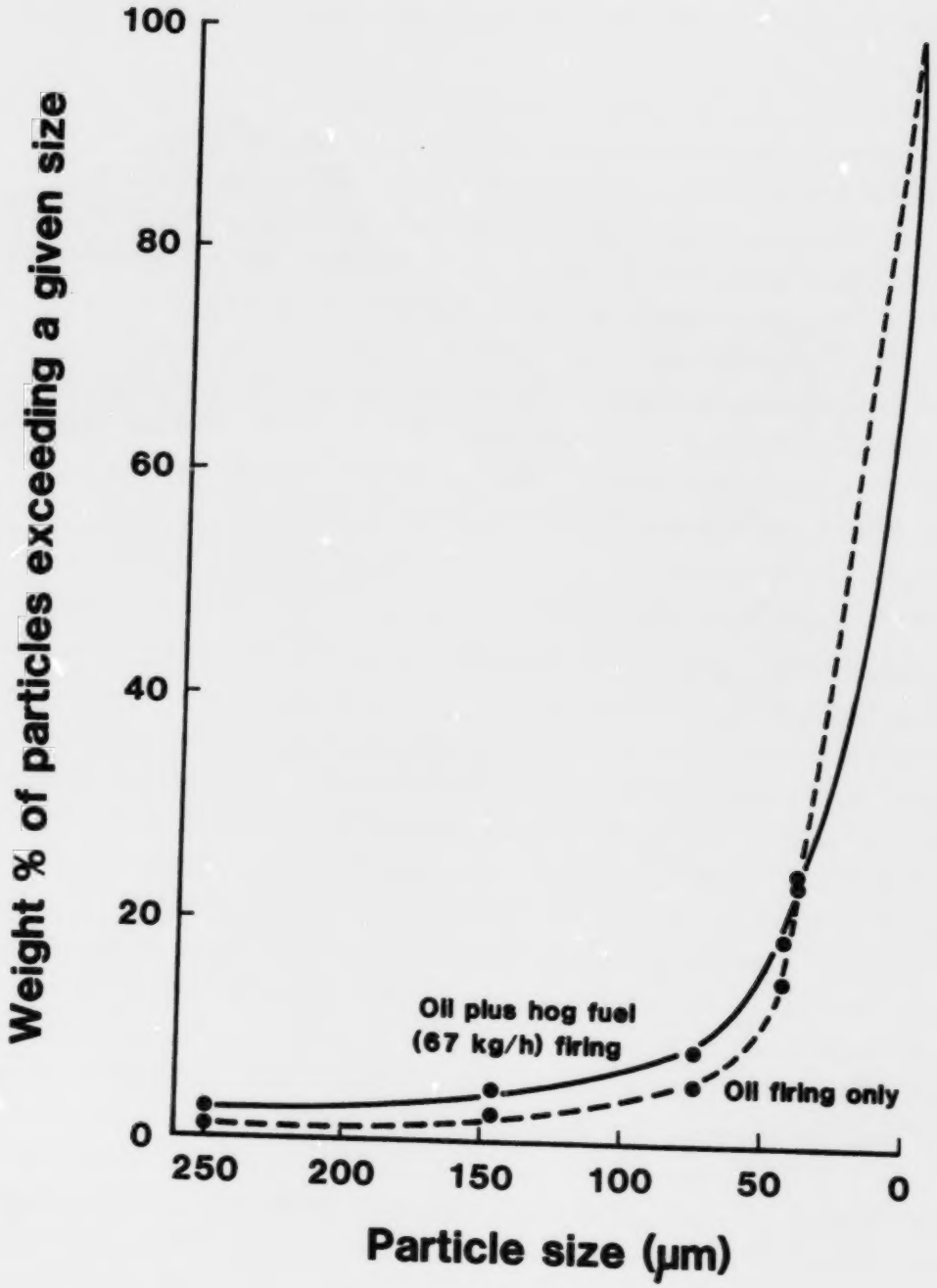

Figure 5. The effects of hog fuel contamination on the cumulative particle size distribution of lime mud. Limes produced in the second run were used in the causticizing.

purge for the inorganic contaminants. However, the removal of the inorganic contaminants would not be complete and they could still accumulate in the lime mud where their removal would likely be difficult [11].

A trace element analysis for the white liquor indicated increases in Al, K, Mn and P and a possible decrease in Si. The latter was not expected based on the solubility of Si and cannot be considered conclusive due to the limited number of tests (see recycle experiments below). The concentration of these elements in a mill liquor system would likely increase and could have an impact on down-stream processes. An increase in aluminosilicate scaling in the evaporators and digester [12] might occur. Also an increase in the recovery furnace carry-over, hence tube fouling, might occur due to the lowering of the smelt melting point by potassium compounds [12,13].

3.3.3 Lime Recycling Studies

Causticizing with limes produced in the pilot kilns could not provide information on the effects of long term use of wood residues in calcination. Therefore, laboratory experiments were conducted in which a kraft mill lime mud was calcined in a laboratory muffle furnace (1100°C), used to causticize a low-sulphidity kraft mill green liquor (AA = 29, EA = 23, TTA = 111) and then recycled. Hog fuel (4% ash) was mixed with the lime mud in a weight ratio of 1:1 (dry basis) prior to calcination to produce a "contaminated" lime. This weight ratio represented over twice the requirement in a mill kiln for 100% replacement of the fossil fuel. Since the input rate of the inorganic contaminants in the laboratory studies was very much larger than would be expected in a mill environment, the effects on the lime quality due to the recycling could be assessed in fewer cycles. A control or "uncontaminated" sample of lime mud was also recycled so that valid comparisons could be made. After each causticizing, the settling characteristics of the lime mud in white liquor were determined and the white liquor analyzed. The fraction of particles exceeding 60 mesh were removed by screening and additional settling studies conducted in water. Prior to

recycling the lime mud, fresh make-up (approximately 12%) was added to replace material lost during handling and removed for further analysis. After the final cycle, filtration experiments were performed.

Recycling the lime mud through four cycles caused the available lime index of the contaminated and uncontaminated limes to decrease by 8.7% per cycle and by 4.2% per cycle respectively. The difference in the two cases can be attributed to the increased accumulation of Mg (32%), Fe (290%), Si (190%), Al (340%), Mn (73%) and P (40%) in the contaminated sample compared with the uncontaminated one. The available lime index was reduced because of the increased "dead load" and the acidic nature of some of these contaminants. Lime might also have reacted with some of these contaminants and in order to investigate this aspect the lime muds were analyzed by x-ray diffraction. Clean patterns were found for $CaCO_3$ which indicated that the impurities were in an amorphous form. However, in the +60 mesh contaminated material from the last cycle CaO, α-quartz, Gaylussite ($Ca\ Na_2(CO_3)_2 \cdot H_2O$), a Na K Al hydrate and $CaSiO_3$ were identified. This indicated that at least some of the impurities were reacting with the lime to form crystalline compounds. It is assumed that the reduction in the available lime index was due to the side reactions of the impurities with the lime, as well as to the acidic nature of some of the contaminants and to the increased "dead load" (dilution effect) as mentioned above. Since the rate of input of these impurities per cycle would be lower in a mill the decrease in the availability would not be as great although the same trends would likely occur.

In the recycling experiments the fraction of lime mud exceeding 60 mesh increased substantially from 0.12% for the uncontaminated sample to 3.1% for the contaminated one (fourth cycle). The +60 mesh contaminated material also contained substantial quantities of Mg (1.2%), Fe (2.2%), Si (4.1%), Al (7.1%), K (2%) and Na (5.4%) and acted as a major purge stream for these contaminants. In a mill environment it would be necessary and relatively easy to remove the particles in this size range ("grits" from the slaker-classifier) in order to reduce the rate of accumulation of inorganic contaminants in the lime mud.

The settling characteristics of lime mud in white liquor and in water were affected only slightly by the contaminants from the hog fuel. The settling characteristics for the laboratory recycled lime muds differ from those produced from the pilot kiln limes and is believed to be due to the difference in calcining conditions, which are known to have an effect upon the settling rates [6,14]. However, the influence of the contaminants cannot be completely discounted since the pilot kiln causticizing studies indicated that the source of the biomass (sawmill wood residue versus hog fuel) had an effect on the magnitude of the settling rate decrease. A mill kiln which previously produced a hard burned lime would likely have a decrease in the settling rate whereas a kiln which previously produced a soft burned lime would likely have very little change.

The filtration characteristics of the lime muds were similar to those of the pilot kiln experiments. The bed formation time and the moisture content of the bed increased (40% and 10% respectively). However, the bed again tended to crack and the permeability dropped only slightly.

The equilibrium causticizing efficiency, as with the kiln limes, was not affected by the inorganic contaminants.

The contamination of the lime by inorganic contaminants from the hog fuel also caused increases in the concentrations of Si (30%), Al (80%) and K (9%) in the white liquor. The concentrations tended to increase with each cycle, even though fresh green liquor was used in each one, and were probably due to the accumulation of these elements in the lime mud. In a mill environment the rate of increase in the concentrations of these elements in the white liquor would not be as great since much less (10-30% of the quantities used in these accelerated laboratory simulation tests) hog fuel would be burned per cycle. The problems which could arise due to these elements have been discussed above.

3.3.4 Effect of Settling Aids

The pilot kiln and recycling experiments indicated that wood residues used in calcination could not only cause increased accumulations of inorganic contaminants in the lime mud cycle but could also adversely effect the settling characteristics of the lime mud. Therefore, the effectiveness of two commercial settling aids (Cato 1511: Nacan Products Ltd. and Percol 725: Alloid Colloids Inc.) were assessed. Pilot kiln lime produced in the first test run using 119 kg/h of wood residue was used to causticize a high-sulphidity kraft mill green liquor. After transferring the contents of the reactor to the settling cylinder one of the settling aids in solution was added in small increments until there was no further increase in the settling rate. The final dosage of the two settling aids tested, Cato 1511 and Percol 725, were 15 ppm and 5 ppm, respectively.

Settling aids improved the settling characteristics of the lime mud as shown in Figure 6, however there were adverse effects on the filtration. The formation time of the lime mud bed increased (by approximately 60%) and the permeability decreased (by approximately 50%). The latter should be considered cautiously due to the tendency of the bed to crack. The moisture content, however, was unchanged. There was also an increase in the fraction of lime mud particles exceeding 400 mesh but the concentrations of the inorganic elements did not change substantially. Since the settling aids were not optimized in terms of molecular weight and ratio of cationic to anionic sites, improvements in settling and filtration characteristics are possible.

4. PROJECTIONS TO MILL KILNS

4.1 Fossil Fuel Savings

Projections concerning the substitution of fossil fuel by hog fuel in a mill kiln are shown in Figure 7 and consider the effective utilization of the hog fuel and increased dusting. In the figure the reference line assumes one GJ from the fossil fuel is equivalent to one

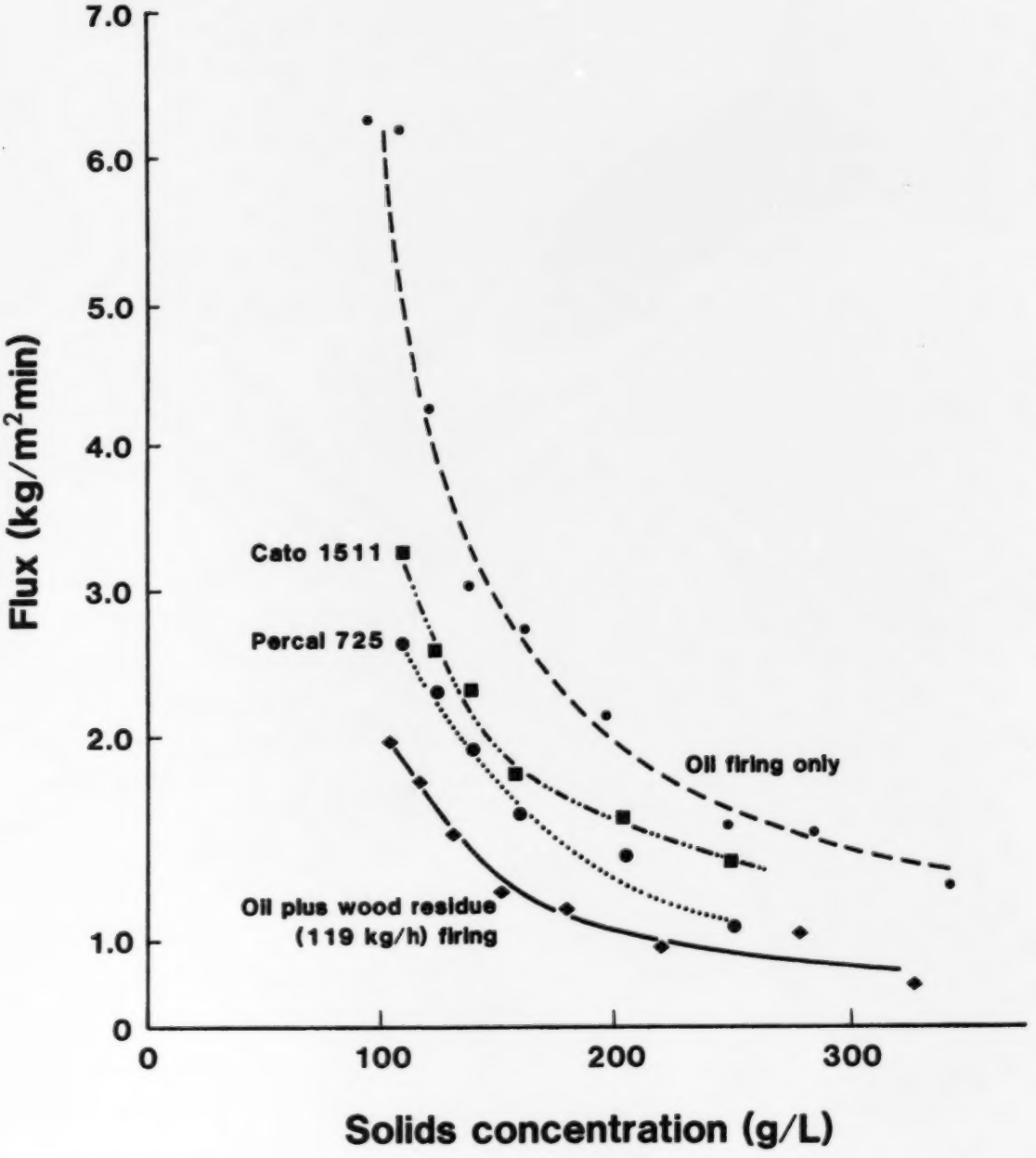

Figure 6. The effects of settling aids on the solids flux in white liquor. Lime produced in the first test run using wood residue at 119 kg/h was used in causticizing. Lime produced with only fossil fuel was included for comparison purposes.

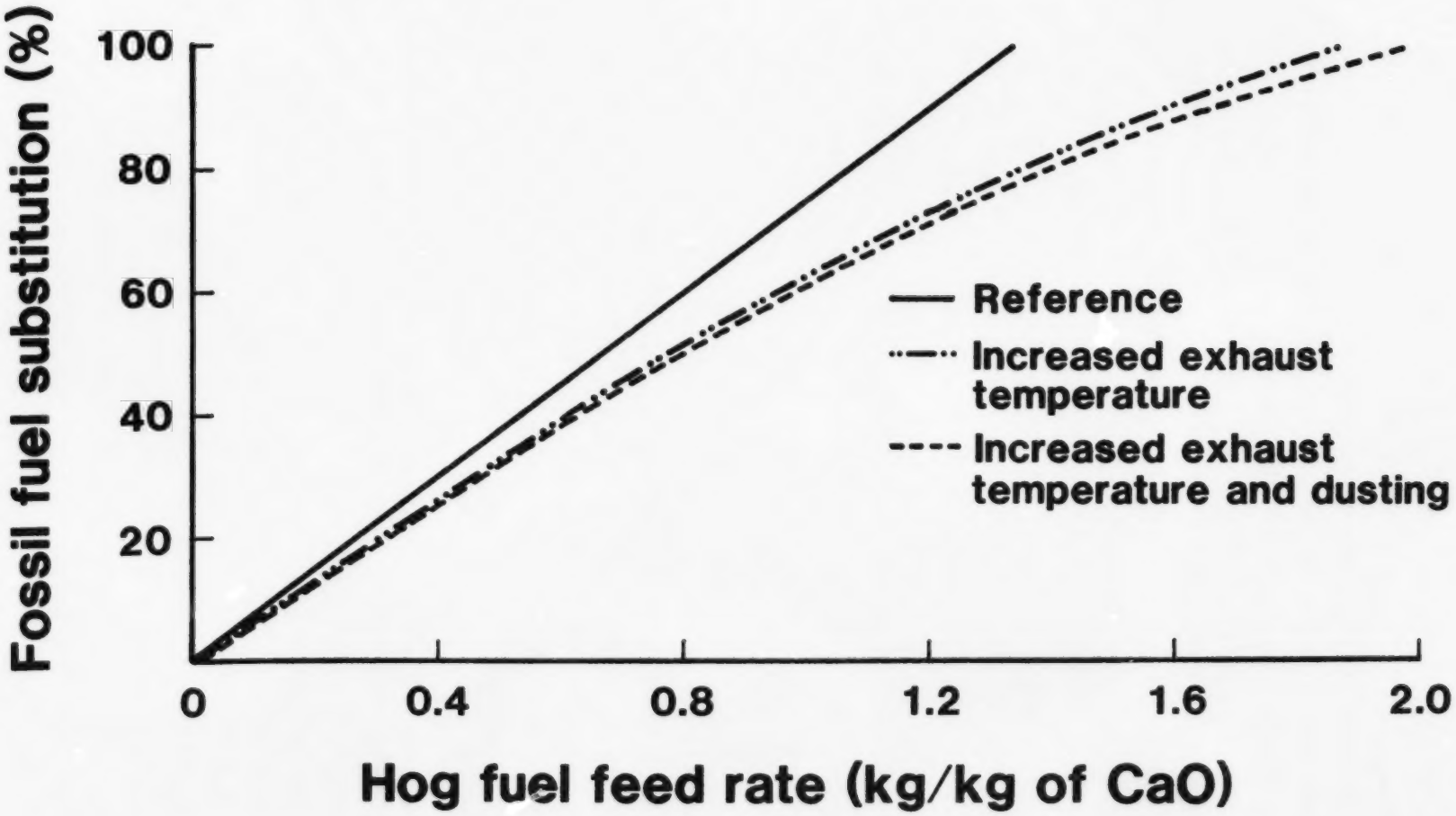

Figure 7. The effects of increased exhaust gas temperature and dusting on the level of fossil fuel substitution in a mill kiln for a given hog fuel (50% moisture) feed rate. The reference line assumes one GJ from fossil fuel is equivalent to one GJ from hog fuel. The effects of the in-situ combustion of hog fuel on flows have been ignored. The hog fuel feed rates of 28 to 101 kg/h (second test run) correspond to the range of 0.6 to 2.4 kg/kg CaO.

GJ from the hog fuel. The exhaust temperature curve accounts for the fraction of hog fuel - based on pilot kiln data - which contributes only to an increase in the exhaust temperature and therefore reflects the effective utilization of the hog fuel. The combined exhaust temperature and dusting curve includes the heat effects of the latter and is again based on the pilot kiln data. However, these projections should be considered cautiously since the pilot kiln data on hog fuel utilization and dusting may not be directly applicable to a mill kiln. Also it was assumed that no feeding or flow problems would occur and that a satisfactory product could be produced. The heat loss from the kiln was also considered constant and the same for all the cases considered. The effects of lime quality on causticizing and the effects of dusting on scrubber and vacuum filter loading were also disregarded.

Of the two factors considered it is evident that the effective utilization of the hog fuel is the more critical.

Although hog fuel feed rates are given in this figure for up to 100% substitution of the fossil fuel it is not very likely that this degree of substitution can be reached. In the case of the pilot kiln test run II-2 approximately 50 kg/h of wet hog fuel (i.e. 1.90 kg/kg CaO) was optimum in terms of its effective utilization, i.e., limited exhaust gas temperature rise and fuel savings (based on long term average product rate). It is most important to note that in order to obtain the same fossil fuel savings (20%) in a mill kiln a hog fuel feed rate of only 0.27 kg/kg CaO (M.C. = 40%) would be required.

Of some uncertainty, however, is the differenc in combustion which may occur when extrapolating from 1.90 to 0.27 kg/kg CaO. In the pilot kiln, char was burning in the firing zone at a hog fuel feed rate of 50 kg/h, but combustion of the char was essentially complete by the middle of the kiln at a hog fuel feed rate of 28 kg/h. The combustion characteristics of the hog fuel in a mill kiln will be dependent upon a number of factors but one cannot be absolutely certain that an adequate temperature profile will be developed at a hog fuel feed rate of 0.27 kg/kg CaO which would allow a 20% reduction in fossil fuel. Of course

in the above it has been assumed that deterioration in flow conditions (affecting product rate) do not dominate.

4.2 Material Flow

It is clear from our tests that the feeding of additional material to a mill kiln will be contingent upon the existence of excess capacity in both solids and exhaust flows, otherwise reduction in production rate may occur, mostly because of the increased exhaust gas flow rate. The latter could be about 10-20% at the 30-50% fossil fuel substitution level. Since hog fuel has a low bulk density relative to lime mud there will be increased congestion in the feed section of the kiln. The additional moisture from the hog fuel will also cause an increase in the exhaust requirements. Since heat losses etc. per unit production will be substantially lower in a mill kiln than in the pilot kiln the problems will not be as severe at the same degree of fossil fuel replacement. This is shown by using Figure 7 and the hog fuel and lime mud feed rates from the second pilot kiln test run. For the hog fuel feed rates employed the corresponding mill kiln fuel savings would be 40% (28 kg/h), 70% (50 kg/h), 80% (67 kg/h) and over 100% (101 kg/h).

A mill kiln operating at full capacity would have an increase in the drop-out and dusting rates as hog fuel is fed to it. An increase in the height of the feed dam could reduce the drop-out rate but at the expense of an increased rate of dust carry-over to the scrubber. Based on the pilot kiln operation, an increase in the rotational speed might also be beneficial since the solids flow would be improved in the feed section, but again problems might occur because of the reduced residence time in the kiln. In the pilot kiln the sticking of material to the refractory prevented it from flowing freely in the middle and firing sections of the kiln and the normal relationship between residence time and rotational speed did not hold.

Substantial coating of the refractory with some ring formation occurred in the pilot kiln. Although this had a severe impact upon the material balance and the results of the relative short pilot studies it

does not necessarily mean a problem in a mill kiln which is normally operated with a coating on the refractory, particularly because the degree of adherence was observed to be relatively low. Also, since a smaller quantity of hog fuel per unit production would be required for the mill kiln compared with the pilot kiln the input rate of low melting point compounds, and hence associated problems, would be reduced.

4.3 Temperature Profile

The in-situ combustion of hog fuel shifts the maximum temperature towards the middle of the kiln at high degrees of substitution and causes increased feed-end temperatures in all cases. Since there is a variation in refractory along the length of a mill kiln its temperature limitations may in turn limit the hog fuel feed rate. Improvements in the refractory could eliminate this problem, but higher exhaust gas temperatures would still be detrimental to solids flow (dusting in the kiln, hence increased loading in the scrubber and the lime mud washer) and equipment (chains and exhaust system). Higher exhaust temperatures, relative to the fossil fuel only case, would also be an indication of poor hog fuel utilization.

4.4 Product Quality

Since a mill kiln would require a much lower hog fuel feed rate per ton of product than the pilot kiln for the same fossil fuel savings the input rate of the contaminants would be reduced. Based on the estimated hog fuel requirements for a mill kiln, the input rate would be reduced by more than 50% for a given level of substitution. However, it should be noted that causticizing the green liquor and recycling the lime mud could exert a dominating influence on the concentrations of impurities.

5. SUMMARY

1. In-situ combustion of hog fuel in the pilot kiln resulted in a temperature increase in the middle and feed end of a pilot kiln

and allowed the lime conversion to be maintained at reduced fossil fuel firing rates.

2. At a hog fuel feed rate of 50 kg/h (wet basis) and a lime mud feed rate of 146 kg/h the reduction in fossil fuel consumption (GJ/t CaO produced), based on a long term average product flow rate, was 12% with a high hog fuel utilization of 90%. The reduction in fossil fuel consumption (average product flow rate basis) at a hog fuel feed rate of 101 kg/h (wet basis) was 21% with a low hog fuel utilization of only 62%. The 50 kg/h hog fuel feed rate corresponds to about 70% of the total fuel requirement of a mill kiln.

3. Feed-end and dusting losses increased as hog fuel was fed to the pilot kiln. In-situ combustion of hog fuel affected the formation of pebble lime and resulted in increased dusting. There was also an increased tendency for material to adhere to the kiln refractory which caused accumulation problems.

4. The in-situ combustion of wood residues in calcination resulted in increased lime reactivity since the degree of over-burning was reduced.

5. The equilibrium causticizing efficiency was not affected by the use of wood residues.

6. The settling characteristics of the lime mud were affected by both the contaminants introduced with the wood residue and the calcining conditions. Unscreened sawmill wood residue (6% ash) produced by dry debarking caused a greater reduction in the settling rate than did a screened kraft mill hog fuel (4% ash) produced by wet debarking. The settling rate was inversely related to the lime reactivity which was affected by calcining conditions. Settling aids improved the settling characteristics.

7. Lime mud filtration was adversely affected by the in-situ combustion of wood residues and could lead to higher moisture contents in the filtered sludge. The settling aids which were tested reduced the mud filtration rates.

8. A build-up of inorganic contaminants occurred in recycled lime mud and could cause an increased loading in the white liquor clarifier, lime mud washer and filter.

9. The use of wood residues caused a slight decrease in the available lime index due to the inorganic contaminants. This was due to some contaminants reacting with lime, their acidic nature, and their dilution effect (dead load). It is imperative that a wood residue with a low dirt content be used in a mill kiln.

10. Causticizing with lime produced by the in-situ combustion of wood residues resulted in increases in Si, Al and K in the white liquor. These increases could cause problems in a mill environment due to increased scaling (evaporators) and fouling (recovery furnace tubes).

11. The use of wood residues in in-situ combustion resulted in an increase in the quantity of coarse material in the lime mud. In a mill environment this would result in an increase in the quantity of grits removed by the slaker-classifier which at the same time would partially remove the inorganic contaminants and thus reduce their rate of build-up in the lime cycle.

12. The in-situ combustion of a dry pelletized biomass did not produce any fossil fuel savings. It caused excessive feed end temperatures and loss of product, as dust, from the feed end of the pilot kiln.

13. The ultimate goal of complete or near-complete substitution of fossil fuel by wood residues can be achieved by additional firing of dried (10-15% moisture content) fines from the hot end of the kiln. Since the latter type of fuel is substantially more costly than wet and noncommimuted hog fuel its usage should be minimized.

6. RECOMMENDATIONS

The pilot kiln calcining and laboratory causticizing studies indi-

cated that the use of biomass for in-situ combustion will cause a number of problems which could limit the replacement of fossil fuel in a mill lime kiln to 30 to 50%. The actual acceptable degree of substitution could depend on both kiln and hog fuel characteristics.

In order to obtain a better assessment of the potential of this approach, the in-situ combustion of hog fuel should preferably be tried in a mill kiln where some excess capacity exists. This will minimize the feed problems which were present in the pilot kiln runs. The lower hog fuel feed rate per unit fossil fuel savings (compared to the pilot kiln) will also reduce the feed problems. The inorganic contamination of the product as well as the adverse effect upon the pebble lime formation can also be expected to be reduced. The rate of material build-up on the kiln refractory will also likely be reduced although long term problems may occur and would need to be assessed carefully at increasing degrees of substitution of fossil fuel.

7. ACKNOWLEDGEMENTS

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APPENDIX A

Operating data and analyses of the first test run.

TABLE A-I

SUMMARY OF MASS AND HEAT BALANCE CALCULATIONS FOR THE FIRST TEST RUN

Run No.	Wood residue feed rate (kg/h)	Mass balance error[1] (%)	Exhaust gas temperature (°C)	Exhaust gas flow[2] (m^3/s)		Kiln heat loss[3] (GJ/h)	Increase in exhaust gas enthalpy flow[4] (GJ/h)
				Standard	Actual		
I-0	0	-18	385	11.75	28.24	1.01	0
I-1	40	-57	405	13.38	33.31	1.28	0.021
I-2	119	-37	615	19.04	62.01	0.96	0.390
I-3	97	-49	500	12.48	35.37	1.03	0.137
I-4	140	-45	700	15.64	55.78	1.12	0.453

[1] Based on calcium
[2] Estimated
[3] Heat loss through kiln shell (estimated by heat balance on kiln)
[4] Relative to fossil-fuel only case (I-0)

TABLE A-II

ANALYSIS OF WOOD RESIDUE ASH (FIRST TEST RUN)

Component	% (wt)
K	1.21
Al	4.50
Mg	0.47
Mn	0.25
Fe	0.89
Ca	5.45
P	0.31
SiO_2	53.00

Note: SiO_2 was determined by wet methods and all other elements by atomic absorption

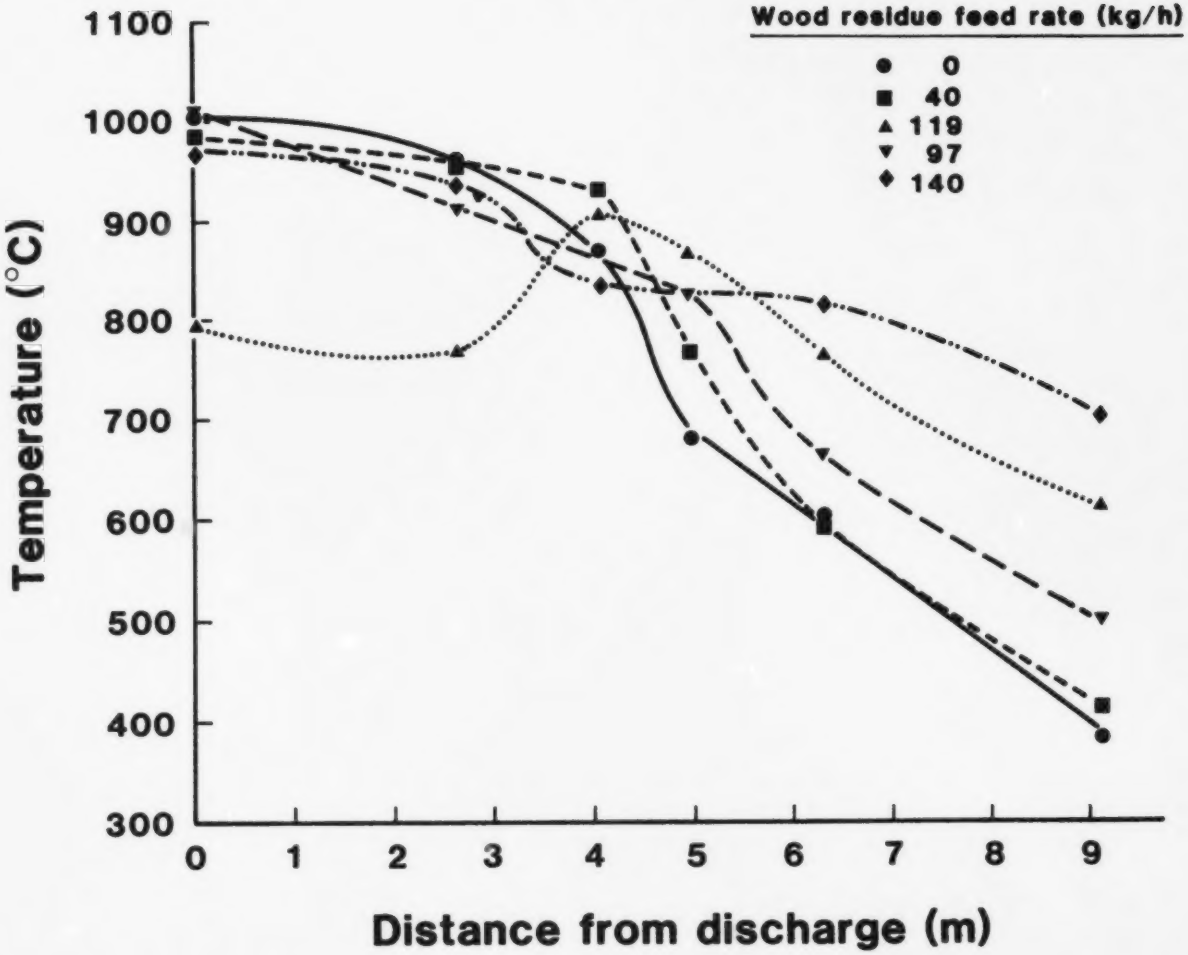

Figure A-1. Kiln temperature profiles during the in-situ combustion of wood residues during the first test run.

APPENDIX B

Operating data and analyses of the second test run.

TABLE B-I

RESULTS (SHORT-TERM TIME INTERVAL) OF THE SECOND PILOT KILN TEST RUN

The data given below are for the lowest oil firing rates obtained.

Hog fuel feed rate (kg/h, wet basis)	Time Interval	Product Rate (kg/h)	ALI (%)[1]	Oil (US gal/h)	Fuel Consumption (GJ/t)[2]
0	Mar 15, 20-22	55.6	64	12.5	47.7
	22-24	44.5	83	13	47.9
	Mar 16, 00-02	42.2	84	13	49.8
	02-04	32.2	87	13.4	64.9
	04-06	44.2	83	13.4	49.6
28	Mar 16, 16-18	24.0	75	11	82.8
	18-20	25.6	84	11	69.4
50	Mar 16, 22-24	20.0	~83	10	82.0
	Mar 17, 00-02	28.8	~80	9.5	56.0
	02-04	22.5	84	9.5	68.4
	04-06	12.7	81	9.5	125.4
	06-08[3]	52.4	70[3]	9.5	35.2
	08-10[3]	58.1	70[3]	9.5	31.7
	10-12[3]	26.5	70[3]	9.5	69.5
	12-14	25.6	81[4]	10	65.4
	14-16	26.5	80[4]	10	64.0
67	Mar 17, 20-22	22.5	82	10	73.8
	22-24	22.2	82	10	74.4
	Mar 18, 00-02	21.3	84	9	75.8
	02-04	25.9	85	9	61.8
101	Mar 18, 12-14	39.9	80[4]	8	29.3
	14-16	11.1	80[4]	8	105.2
	16-18	34.2	80[4]	8	34.1

[1] ALI = available lime index.

[2] Fuel consumption (GJ/t) is based on a tonne of "available" lime in product actually collected.

[3] Temperature profile had collapsed during these times, and material dropped from the walls and caused an increase in the product flow rate. The available lime index was not measured and is assumed to be approximately 70%, based on loss on ignition data.

[4] ALI's are estimated from the loss on ignition data.

TABLE B-II

SUMMARY OF MASS AND HEAT BALANCES CALCULATIONS FOR THE SECOND TEST RUN

Run. No	Hog fuel feed rate (kg/h)	Mass balance error[1] (%)	Exhaust gas temperature (°C)	Exhaust gas flow[2] (m^3/s)		Kiln heat loss[3] (GJ/h)	Increase in exhaust gas enthalpy flow[4] (GJ/h)
				Standard	Actual		
II-0	0	-18	410	11.85	29.62	1.11	0
II-1	28	-33	450	12.39	33.00	1.07	0.053
II-3	50	-27	500	12.64	35.71	1.01	0.105
II-4	67	-29	560	14.04	42.60	1.09	0.190
	101	- 4	680	15.38	53.45	0.94	0.385

[1] Based on calcium
[2] Estimated
[3] Heat loss through kiln shell (estimated by heat balance on kiln)
[4] Relative to fossil fuel-only case (II-0)

TABLE B-III

SUMMARY OF OPERATING CONDITIONS FOR THE SECOND TEST RUN USING WOODEX TO REPLACE OIL

Woodex feed rate (kg/h)	Fuel consumption (GJ/t)	Exhaust gas temperature (°C)
30	69	610
45	63	820
69	62	915
85	66	895

TABLE B-IV

ANALYSIS OF HOG FUEL ASH (SECOND TEST RUN) USING X-RAY METHODS

Component	% wt.
SiO_2	1.58
Al_2O_3	0.44
Fe_2O_3	0.27
CaO	87.68
MgO	3.98
K_2O	0.82
Na_2O	0.38
SO_3	0.54
P_2O_5	2.98
TiO_2	0.01
Mn_2O_3	1.40

TABLE B-V

SCREEN ANALYSIS OF HOG FUEL (SECOND TEST RUN)

Tyler Screen	% wt.
-3/4 + 1/2 inch	16.4
-1/2 + 3/8 inch	13.1
-3/8 + 1/4 inch	33.1
-1/4 + 4 mesh	9.5
- 4 + 6 mesh	12.7
- 6 + 8 mesh	6.4
- 8 + 10 mesh	2.3
-10 + 14 mesh	1.4
-14 + 20 mesh	1.4
-20 + 28 mesh	0.9
-28 + 35 mesh	0.9
-35 + 48 mesh	0.9
-48 + 65 mesh	0.5
-65 + 100 mesh	0.5
-100 mesh	Trace

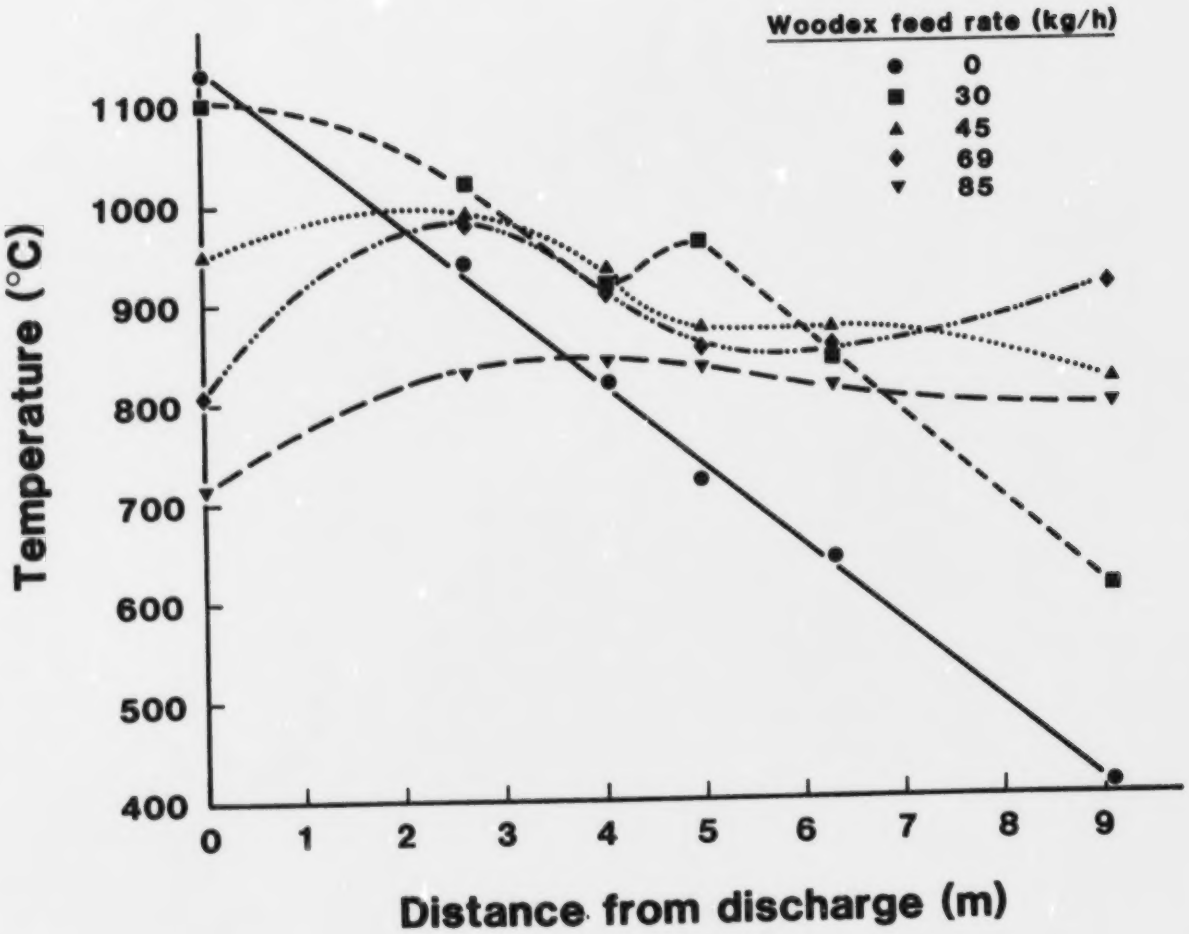

Figure B-1. Kiln temperature profiles during the in-situ combustion of Woodex in the second test run.

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